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Multi–Epoch Mid–Infrared Interferometric Observations of the Oxygen-rich Mira Variable Star RR Aql with the VLTI/MIDI Instrument

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Abstract. This work is part of an on-going program of multi-epoch simultaneous observations of a sample of four evolved stars — RR Aql, GX Mon, S Ori, and AH Sco — using the VLTI and VLBA facilities. Different pulsating layers and their relative positions are monitored across phases and cycles. Here, we present mid-infrared interferometric observations of the oxygen-rich Mira variable RR Aql at 13 epochs covering 4 pulsation cycles with the MIDI instrument at the VLTI. We modeled the observed data using dust-free self-excited dynamic model atmospheres combined with an ad-hoc radiative transfer model of the dust shell. This study represents the first comparison between interferometric observations and dynamic models over an extended range of pulsation phases covering several cycles. We show that the combination of the models describe the observed data well. We determine the best dust-free dynamical model atmosphere and the best dust shell parameters including the optical depth of the two examined dust species (Al_2O_3 and silicates), the inner boundary radii of the dust shells, the density distribution, and the continuum photospheric angular diameter for all epochs. The results indicate that silicate is the major chemical component in the dust shell. We also compare the data with equivalent uniform disk (UD) and Gaussian FWHM diameters.

1. Introduction

In spite of extensive research, many aspects of the physical processes occurring during the late stages of the stellar evolution remain unknown. In particular, the extensive mass loss typical for stars on the asymptotic giant branch (AGB) is still under intense investigation. The mass loss can reach up to 10^{-4} $M_\odot yr^{-1}$ (Matsuura et al. 2009) and thus becomes an important source of gas and dust in galaxies. AGB stars are low to intermediate mass stars (0.6–10 $M_\odot$) that are characterized by high luminosities and large diameters. These properties make them ideal targets for interferometric observa-

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14. ABSTRACT
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tions. At near-infrared wavelengths, interferometric observations provide information concerning the conditions near the stellar surface. At mid-infrared wavelengths, interferometric observations are well suited for studying molecular layers and surrounding dust formation zones. Radio interferometry allows one to study the properties of the circumstellar environment by probing the maser radiation emitted by molecules such as SiO, H_2O, and OH.

We have established concurrent multi-epoch observations of evolved stars with near-infrared, mid-infrared and radio interferometry using optical long-baseline interferometry with AMBER and MIDI at the VLTI, and additionally radio interferometry (MERLIN and VLBA). Our sample includes four evolved stars, the three Mira variables RR Aql, GX Mon, and S Ori and the supergiant AH Sco. The objective of this project was the simultaneous observation of the targets at different wavelengths to probe the different layers of the atmosphere and circumstellar envelope. Concurrent multi-wavelength observations covering many different phases of pulsation are ideally suited for such investigation. Our goal is to study the connection of the pulsation mechanism to the dust condensation sequence and thus to better understand the mass-loss process. Previous results from this program of joint VLTI/VLBA observations for the Mira star S Ori can be found in Boboltz & Wittkowski (2005) and Wittkowski et al. (2007). Here, we report on results of multi-epoch VLTI/MIDI observations of RR Aql (Karovicova et al. in prep.). The coordinated long term VLBA observations, which offer complementary information about the spatial structure and kinematics of the maser spots (SiO and H_2O maser molecules), will be presented in a following paper.

2. VLTI Observations

We obtained 57 spectrally-dispersed mid-infrared interferometric observations of RR Aql with the VLTI/MIDI instrument. RR Aql is an oxygen-rich Mira variable with spectral type M6e–M9 and period of pulsation P = 394.78 days (Samus et al. 2004). RR Aql shows a strong silicate emission feature in its mid-infrared spectrum (Lorenz-Martins & Pompeia 2000). In addition, it has relatively strong SiO, H_2O, and OH maser emission (Benson et al. 1990). The observations were conducted with MIDI, the mid-infrared interferometric instrument (Leinert et al. 2003) that combines two telescopes of the VLTI (Glindemann et al. 2003) and provides spectrally resolved visibilities and fluxes in the 10 μm window (N band, 8–13 μm). The data were obtained under different baseline configurations using either the Unit Telescopes (UTs, 8.2-m), or the Auxiliary Telescopes (ATs, 1.8-m). We used the PRISM as a dispersive element, and the beams were combined in *High_Sens* mode. The observations were combined into 13 epochs covering 4 pulsation cycles between Apr. 9, 2004 and Jul. 28, 2007. The data were reduced using the MIA+EWS software package, version 1.6 (Jaffe, Koehler, et al.[1]).

3. Modeling of the Molecular Layers and Dust Formation Zones

We modeled the data using self-excited dust-free dynamic model atmospheres describing the stellar photosphere and overlying molecular layers (P and M series) by Ireland

[1] http://www.strw.leidenuniv.nl/~nevec/MIDI

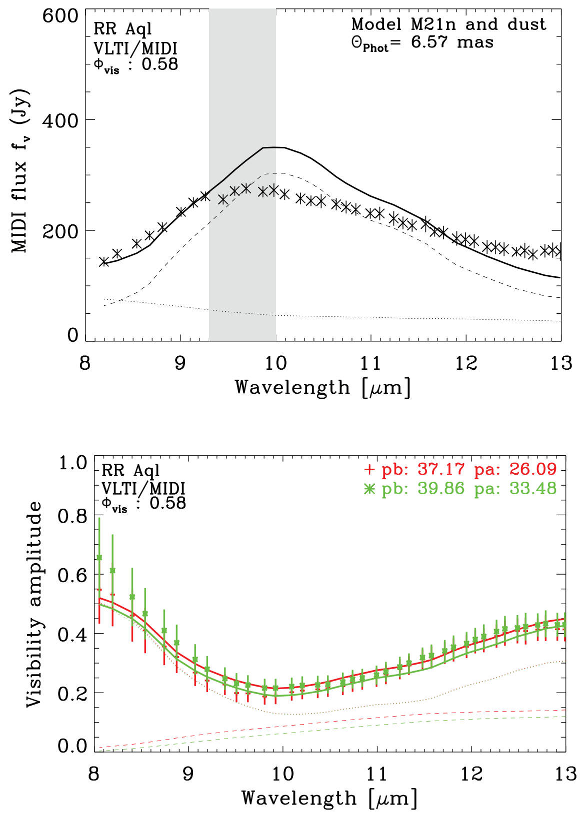

Figure 1. Calibrated MIDI flux spectrum (*top*) and visibility amplitude (*bottom*) as a function of wavelength for epoch A at stellar phase 0.58. The example includes two observations. The plots show the MIDI measured data (crosses with error bars) compared to the combination of the dust-free dynamic model atmosphere (representing the star) and the radiative transfer model (representing the dust shell). The model is indicated by the solid line. The star and the dust contributions are indicated by the dotted and dashed lines, respectively.

et al. (2004a,b). The dust-free dynamic model was complemented by an ad-hoc radiative transfer model of the dust shell using the radiative transfer code mcsim_mpi by Ohnaka, Scholz, & Wood (2006). We examined two dust species of silicate and Al_2O_3 grains. Additionally we compared the data with basic models of the uniform disk (UD) and Gaussian FWHM diameter.

4. Results

The *N*-band spectra show a typical silicate feature around 9.5 μm (Figure 1, top). RR Aql is characterized by a partially resolved stellar disk including atmospheric layers, with a typical drop in the visibility function around 10 μm, where the flux contribution of the silicate emission is the highest and, at the same time, the flux contribution of the star relative to the total flux decreases (Fig. 1, bottom). Beyond ~ 10 μm,

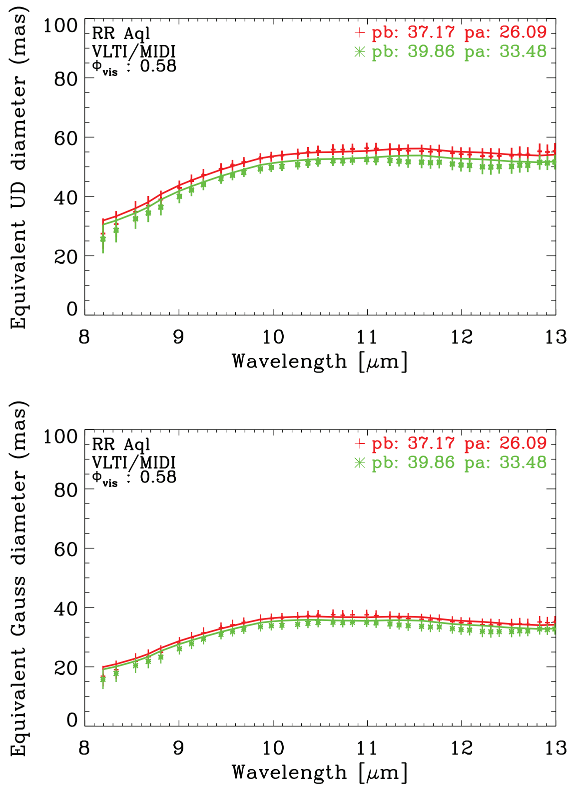

Figure 2. The equivalent UD diameter (*top*) and Gaussian FWHM diameter (*bottom* as a function of wavelength for epoch A at stellar phase 0.58. The MIDI data (indicated by the crosses with error bars) are compared to the combination of the dust-free dynamic model atmosphere and the radiative transfer model (solid line).

the spatially resolved radiation from the optically thin dust shell starts to be a notable part of the observed total flux, and the visibility function increases. We assign rough estimates of the characteristic size of the target using the basic models of the equivalent UD diameter (Fig. 2, top) and Gaussian FWHM diameter (Fig. 1, bottom).

In order to investigate visibility variations during one or several stellar pulsation cycles, the individual observations were combined into groups with similar projected baselines (pb ± 10 %), position angles (PA ± 10 %), and pulsation phases (Φ_{vis} ± 0.15). The data-sets within these groups were averaged, and the uncertainty was computed from the scatter of the averaged values. The *N*-band fluxes were combined into groups with similar phases (Φ_{vis} ± 0.15). The uncertainties on the averaged photometries are mostly systematic, and include the standard deviation and the intrinsic uncertainties of individual observed values, which are large in several cases.

The observations obtained show no sign of intra-cycle or cycle-to-cycle visibility variations. The data do show intra-cycle or cycle-to-cycle *N*-band flux variations. The observations imply that either the molecular and dusty layers stay stable at mid-infrared wavelengths and the radiation from the underlying pulsating star is re-emitted by the dust, or that the observations are not sensitive to variations of these layers. This finding is consistent with simulations using different combinations of the dust-free dynamic model and the radiative transfer model of the dust shell. The comparison of observations and models yields measurements of the chemical composition, radial distributions, and inner boundary radii of the dust shells. We derived for each epoch the best fitting M model, the optical depth of Al_2O_3, the optical depth of silicates, the inner boundary radii, the density gradient, and the continuum photospheric angular diameter. The data suggest that the dust shell of RR Aql can be well modeled using silicate grains alone. This is in agreement with a study of IRAS LRS spectra of AGB stars including RR Aql by Lorenz-Martins & Pompeia (2000). We have also estimated average parameters describing a mean phase of the observed data.

5. Summary and Outlook

We confirm that the combination of the dust-free dynamical model atmospheres *and* the radiative transfer code reproducing the circumstellar dust shell can reproduce the global shape of both the photometry and the visibility spectra very well. The data do not show any phase dependence of the dust formation.

The next step will be to study our recent *H*- and *K*-band VLTI/AMBER observations of RR Aql. AMBER observations have been conducted at two different baseline configurations, and will add independent estimates of the continuum photospheric angular diameter. This, along with our radio interferometric VLBA observations, will contribute to more precise estimates of dust-forming episodes connected to the pulsation mechanism.

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